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# A PROPOSAL FOR DEVELOPING A HURRICANE PLAN WITH A BUILT-IN DECISION-MAKING CAPABILITY



by

Max J. Cleveland
Operations Analyst

Approved by
John P. Michalski
Acting Director
Operations Analysis Office

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Air Force Missile Test Center
Patrick Air Force Base
Florida

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## A. SUMMARY

### 1. Objectives

This study originated as an effort to determine a statistical measure of the ability of weather forecasters to prognosticate the movement of tropical storms and hurricanes in the Caribbean Sea area. The knowledge thus gained was exploited into the formulation of a scheme which provided a probability basis for deciding if and when storm preparations should be made. This scheme made it feasible to construct a hurricane plan with hedging characteristics; that is, a plan which provided for the gradual, but only as necessary, closing down of the base due to storm preparedness. The objectives of this paper are to present: (1) the results of the statistical study, (2) the probability scheme developed for preparedness decision-making, and (3) the outline for developing a hurricane plan with hedging characteristics which incorporates the decision-making mechanism.

### 2. Conclusions and Recommendations

Prognostication errors were determined by comparing prognosticated positions for the storm with corresponding actual positions. The displacement between each pair of such positions was resolved into east-west and north-south components of error. An analysis of these errors revealed that they could be considered as being bivariate circularly normally distributed with equal means. Thus, a circle drawn around a prognosticated storm position, adjusted for bias (i.e., for the error means), would contain the actual storm position a certain percent of the time--the percentage depending upon the size of the circle.

If the radius of the above circle is represented as $c\sigma$, where c is a constant and $\sigma$ is the common standard deviation of the error components, then the percent of time that the actual position will be so contained is given by

$$100p = 100(1-e^{-c^2/2}).$$

The best estimates of $\sigma$ and the mean errors are given below:

| Forecast Period (hrs) | Mean Error* (n.m.) | Standard Deviation (n.m.) |
|---|---|---|
| 12 | -7 | 55.8 |
| 24 | -10 | 90.2 |
| 48 | -48 | 118.9 |

*Negative values indicate that the actual position was, on the average, south and east of the prognosticated position.

By employing a wind-speed isogram, drawn for the forecast period of interest, and the above knowledge concerning the prognostication errors, it is possible to compute the probability that the wind speed at a base will exceed a given amount at the end of the forecast period. Comparison of this probability with a "critical" probability can be used as the basis for deciding if states of storm preparedness should be set or not.

It is proposed that reference values for the "critical" probability be established by computing the ratio of the buttoning-unbuttoning costs to the anticipated repair costs for being caught underprepared.

In order to economize on the effort and money expended on making and unmaking storm preparations and to minimize the interference with missile testing caused by such preparations, it is proposed that a hurricane plan be developed which contains a set of states of storm preparedness instead of just one state. Each state of preparedness should represent protection against a specified range of wind speeds. Such a hurricane plan could and should incorporate the decision-making mechanism discussed above.

## B. DISCUSSION

### 1. Introduction

The Air Force Missile Test Center with its installations in Florida and its Atlantic Missile Range extending down through the Caribbean Sea is seasonably threatened by tropical storms and hurricanes. One of the major problems associated with these storms is that, because of the uncertainties regarding future movement and strength, there is always a question of should the Center be tightly buttoned-up in anticipation of being hit by very severe winds (and by when should this be accomplished), or should only a few precautionary steps be taken (and for how long can they be safely delayed). In other words, when and to what degree should a state of storm preparedness be established at the Center, or at one or more of its associated stations.

Ideally, only those storm preparations should be made that are really necessary to minimize storm damage. Unfortunately, these can not be determined in advance. Accordingly, the Commander, or his representative, proceeds to weigh the various factors involved and trys to arrive at a reasonable decision. Some of the major factors which may influence this decision are: (a) the reported position, movement, and strength of the storm, (b) the labor and material costs for buttoning and unbuttoning the base, (c) the curtailment of missile testing which would result from closing down the range facilities, (d) the setbacks in missile programs which would be caused by removing missiles from their launch pads for storage, by missing opportune moments to launch, etc., (e) the possible repair and replacement costs due to damages to missiles and facilities as a result of underpreparation, (f) the possible delays in missile programs if the missiles were damaged, and (g) national censure if caught underprepared.

Some idea as to the order of magnitude of costs involved at AFMTC can be obtained by considering some of those encountered as a result of Hurricane "Donna" (Sept. 1960). The cost of preparing Patrick Air Force Base and the Cape Canaveral Missile Test Annex for Donna, as reported by the range contractor (Pan American Airways), was $98,000. The Air Force spent an additional $10,500 in buttoning-up PAFB and in the evacuation of its aircraft. According to the cleanup and repair costs following Donna, it appears that even more should have been spent as one tracking facility alone was so badly damaged that some $83,000 was needed for repairs.

One of the requirements which the Commander laid on his staff after Donna had passed was the establishment of confidence limits on the ability of the Weather Bureau to prognosticate the movement of tropical storms and hurricanes. This job was given to the Operations Analysis Office. For the initial effort* the only storm positioning data available

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*AFMTC Operations Analysis Working Paper 60-5, "A Method for Establishing Confidence Limits on Hurricane Forecasting", November 1960.

was that from Donna. Additional data have since been received from the Air Force Hurricane Liaison Officer at the U. S. Weather Bureau Office in Miami, Florida and have been analyzed. The purpose of this report is to present the results of this analysis and to describe a method for utilizing these results to good advantage.

2. Historical

Probably the most important source of weather information is the Air Force Hurricane Liaison Officer with the U. S. Weather Bureau Office in Miami, Florida. Whenever a tropical depression develops into a tropical storm (maximum surface winds from 34 to 63 kts) or into a hurricane (maximum surface winds of 64 kts, or more) the Weather Bureau commences to issue storm advisories at six-hour intervals. These are continued until the storm ceases to be a threat. Concurrently, the Air Force Hurricane Liaison Officer issues an Air Force Hurricane Advisory to all Air Force activities concerned. This advisory includes storm movement and wind velocity data. In particular, the storm's present position and the prognosticated positions for 12 and 24 hours hence are given.

The Liaison Officer also issues an Outlook at 12-hour intervals which gives the prognosticated position for 48 hours hence and the intensity and directional trends for the next 48 to 72 hours. However, this has been issued only since the beginning of 1960 and then only when Florida was threatened.

Beginning with the 1961 hurricane season, and under certain conditions, the Liaison Officer also issued hourly estimates of the storm's position. These conditions were that the storm be within 200 miles of U. S. territory and under surveillance by land based radar or by reconnaissance aircraft.

The PAFB Weather Group supplies the Commander with other valuable weather data. One important piece of such data is the wind-speed isogram which shows the distribution of surface wind speeds around the center of the storm. These are usually drawn for both the sustained speeds and the maximum gusts and are revised as often as deemed necessary. They are also forecasted for 24 and 48 hours hence.

It is the responsibility of the Deputy Chief of Staff, Operations, acting for or at the direction of the Commander, to decide when and if the various hurricane conditions should be established and what other precautionary measures should be taken. This requires a careful weighing of all available weather data and the factors described in the Introduction. However, it often resolves itself into a "seat of the pants" judgment. It is felt that the procedures described herein will ease the judgment problem by providing a statistical basis for decision making.

3. Analysis of Prognostication Errors

Prognostication errors were determined by comparing the prognosticated positions for the storm with the corresponding actual positions. The displacement between each pair of positions was resolved into east-west (x) and north-south (y) components. These components were then analyzed on a statistical basis.

Details of the statistical analyses of the prognostication errors can be found in Appendix A but a brief summary is presented below:

(1) The differences between years were not significant.

(2) The differences between geographical areas were not significant.

(3) The differences (means and variances) between components were not significant.

(4) The correlations between components were not significantly different from zero.

(5) The components, individually, were normally distributed.

In view of the above findings, the data for all years and areas were pooled and the mean and standard deviations determined. The results are presented in Table 1.

TABLE 1

MEANS AND STANDARD DEVIATIONS FOR THE COMPONENTS OF PROGNOSTICATION ERROR

| Forecast Period (hrs) | Mean Error* (n.m.) | Standard Deviation (n.m.) |
|---|---|---|
| 12 | $\bar{x} = \bar{y} = -7$ | $\sigma_x = \sigma_y = 55.8$ |
| 24 | $\bar{x} = \bar{y} = -10$ | $\sigma_x = \sigma_y = 90.2$ |
| 48 | $\bar{x} = \bar{y} = -48$ | $\sigma_x = \sigma_y = 118.0$ |

*Negative values indicate that the actual position was, on the average, south and east of the prognosticated position.

Since the components were individually normally distributed and were uncorrelated, it seemed reasonable to consider that they had come from a bivariate circular normal population. Thus, if we assume that prognostications in the future will follow the pattern evidenced here, we can use the values of Table 1 for making probability statements concerning how close the actual storm position will be to the prognosticated position at the end of the forecast period. In particular, if we draw a circle of radius d around a prognosticated position that has been adjusted for bias (i.e., the error means), the probability that the circle will contain the actual position at the end of the forecast period will be given by

(1) $$P = 1 - e^{-\frac{1}{2}\left(\frac{d}{\sigma}\right)^2}$$

where $\sigma = \sigma_x = \sigma_y$.

4. Application of Error Analysis

a. Computation of threat probabilities.

Plots of equation (1) for the three forecast periods are shown in Figure 1. These curves can be used in conjunction with the wind-speed isogram to compute the approximate probability that the wind-speed at a selected geographical location will be in excess of a specified speed at the end of the forecast period. (A wind-speed isogram is simply a series of isotachs drawn around the eye of the storm. An example is presented as Figure 2a.) The procedures for making the probability calculations are as follows:

(1) Draw the wind-speed isogram, forecasted for the time period of interest, to the same scale as the map being used for plotting the hurricane track.

(2) Rotate the isogram through 180° and superimpose it on the map with the "eye" of the storm coinciding with the location of the installation to be protected. See figure 2b. Each rotated isotach now represents the locus of positions where the storm has to be in order for the wind

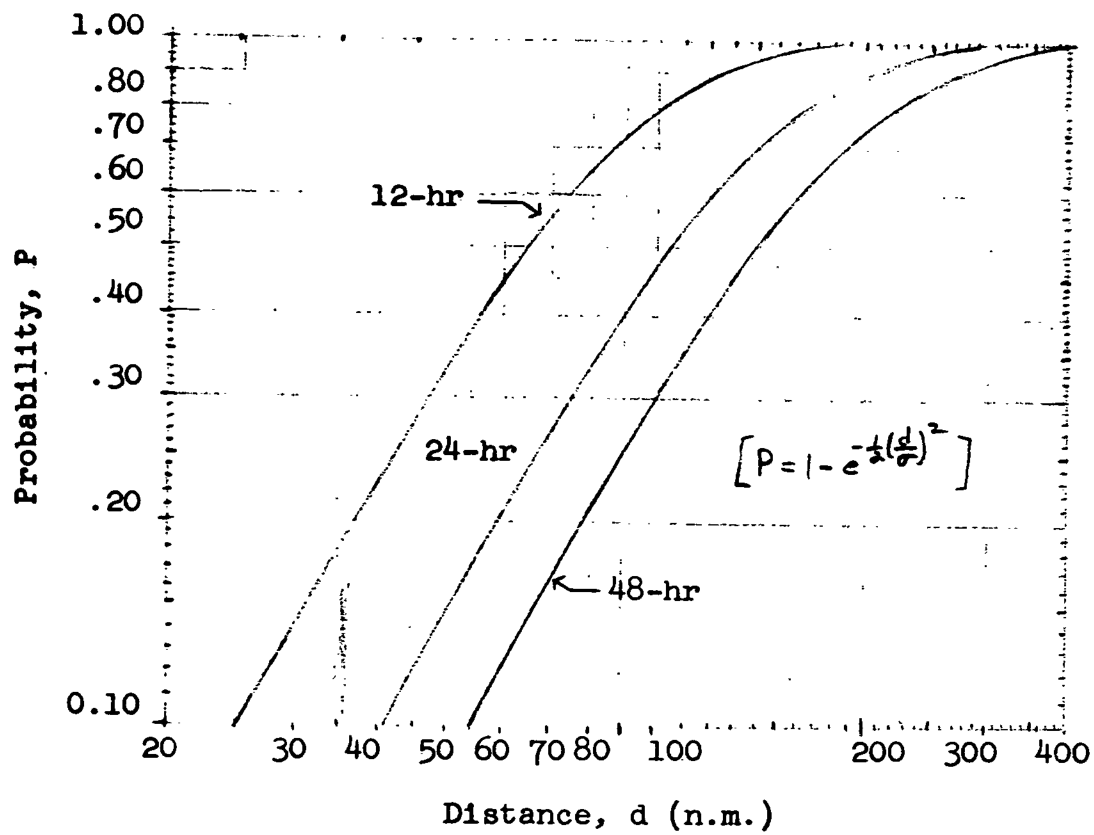


FIGURE 1

Probability that the storm center will lie within d nautical miles of the adjusted prognosticated position at the end of the forecast period.

speed represented by that isotach to occur at the installation. For example, if the storm center was anywhere along the outer rotated isotach of Figure 2b, winds of 20 kts would be occurring at Cape Canaveral.

(3) Plot the prognosticated position of the storm for the time period of interest. Adjust this position for bias, i.e., by the appropriate error means of Table 1 (interpolate or extrapolate, as necessary, for periods other than 12, 24, or 48 hours).

(4) Measure the distances, $d_1$ and $d_2$, from the adjusted prognosticated position to the nearest and farthest points, respectively, on the appropriate rotated isotach. See Figure 2b where use of the 30 kt isotach is illustrated.

(5) Employ Figure 1 for determining the probabilities, $P_1$ and $P_2$, that the storm center will lie within distances $d_1$ and $d_2$, respectively, of the prognosticated position at the prognosticated time.

(6) Determine the areas, $A_1$ and $A_2$, enclosed by circles of radii $d_1$ and $d_2$, respectively. A graph was prepared for this purpose and is presented as Figure 3.

(7) Estimate the area, S, enclosed within the rotated isotach of interest. This can be accomplished readily by estimating the size circle needed to enclose the same area as the isotach and then using Figure 3 to determine the area of this circle.

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FIGURE 2A

A typical wind-speed isogram

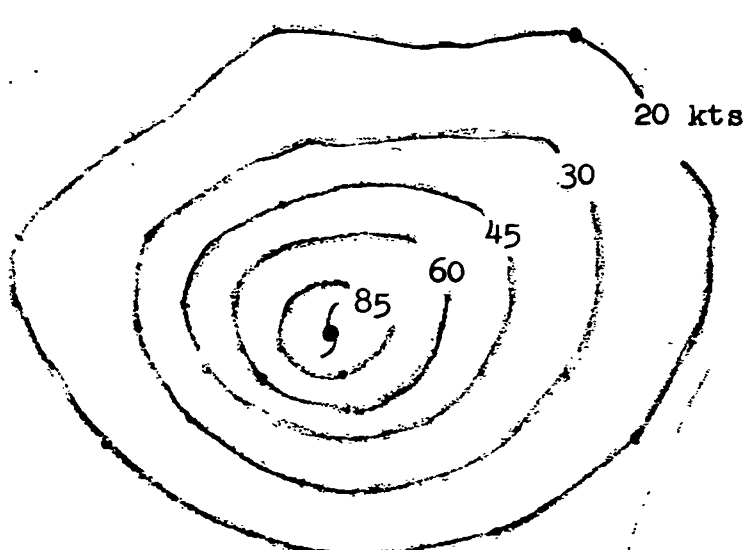
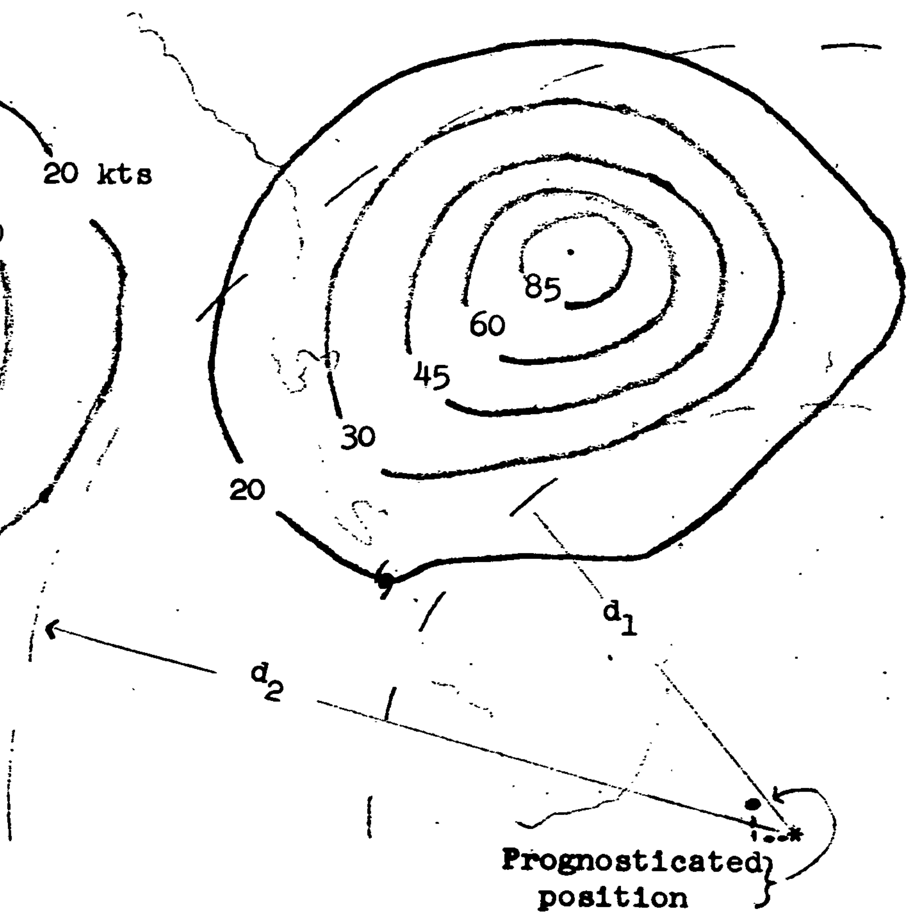



FIGURE 2B

Rotated isogram placed over Cape Canaveral.



Graph for computing areas of circles

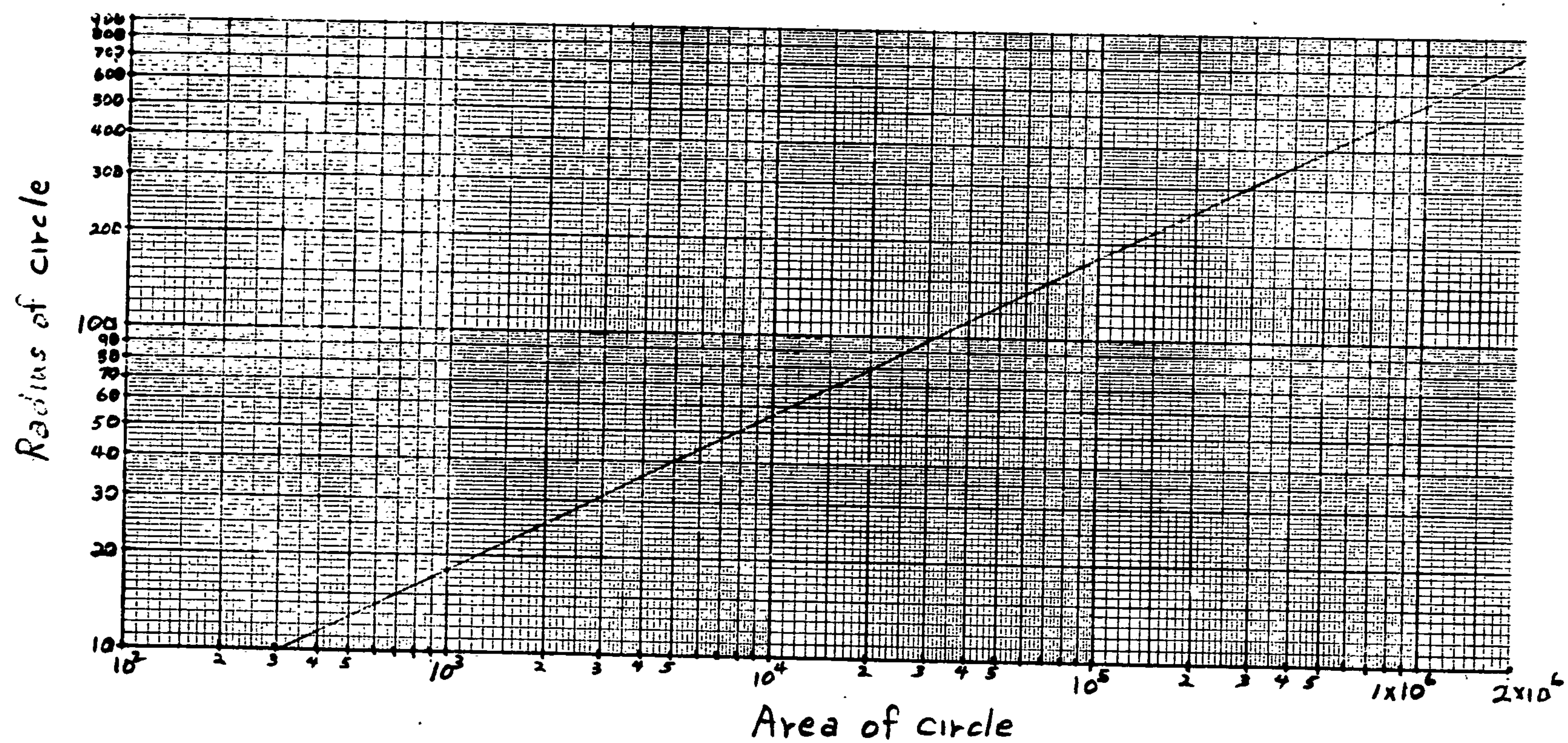



FIGURE 3

(8) Determine the ratio $F = S/(A_2 - A_1)$. A nomogram was prepared for this purpose and is presented as Figure 4.

(9) Compute the "threat" probability, p, from the equation

$$p = F\ (P_2 - P_1). \tag{2}$$

The above "threat" probability represents an approximation to the probability that the storm center will lie inside the selected rotated isotach at the end of the time period of interest. This, in turn, means that p is the probability that the winds at Cape Canaveral, for example, will be in excess of the speed represented by that isotach at the end of that time period.

The threat probability can be used as the basis for deciding whether or not to set a given state of storm preparedness. It is compared with a previously determined critical probability--a different one for each state of preparedness. If it exceeds the critical probability, we set. If it does not, we don't. Details on how the comparisons should be made and how reference, or base, values for the critical probabilities can be determined are contained in later sections.

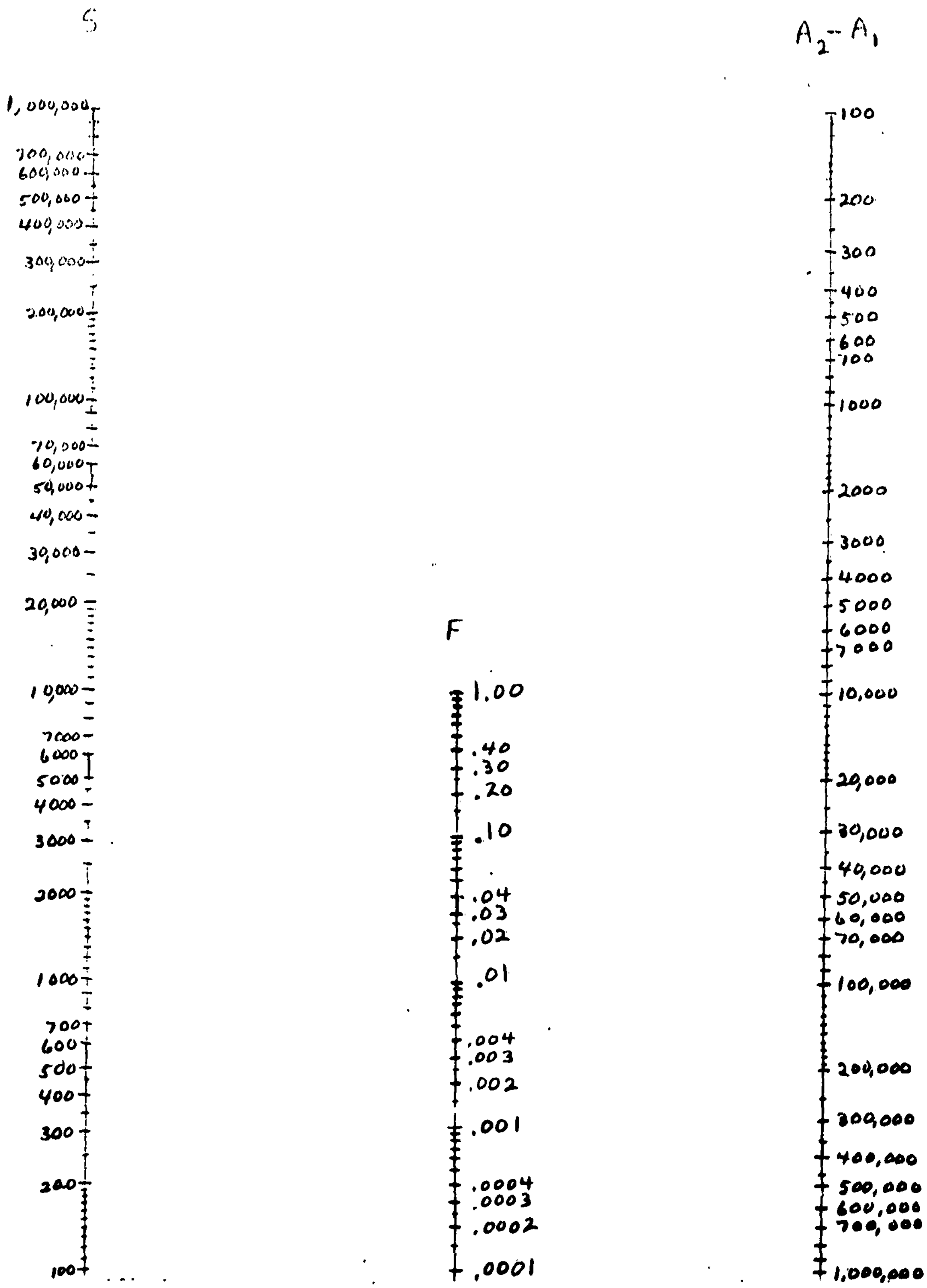



FIGURE 4

Nomogram for computing ratio $F = \dfrac{S}{A_2 - A_1}$

b. Construction of a probability envelope

Establishing confidence limits on the forecasted path of the storm represents another way in which the knowledge gained from the analysis of prognostication errors can be put to good use. We have seen that around any adjusted prognosticated position it is possible to construct a circle which will, with probability P, contain the storm center at the end of the forecast period. If there were many forecast periods (e.g., one-hour, two-hour,....., n-hour) instead of only a few, we could construct a series of such circles whose envelope with probability P, approximately, would contain the storm center for n-hours.

Even with the few forecast periods available, we can make a reasonable approximation to the above probability envelope. We first construct the appropriate circle about each of the prognosticated positions. (The radii of the circles are determined from Figure 1 according to the confidence level desired.) We then draw tangent lines to these circles from the current position of the storm. An example of this construction is shown in Figure 5.

5. Hurricane Plan Development

The philosophy of most hurricane plans is that only one state of storm preparedness is necessary. That is, the base is either completely unprepared or it is prepared to the

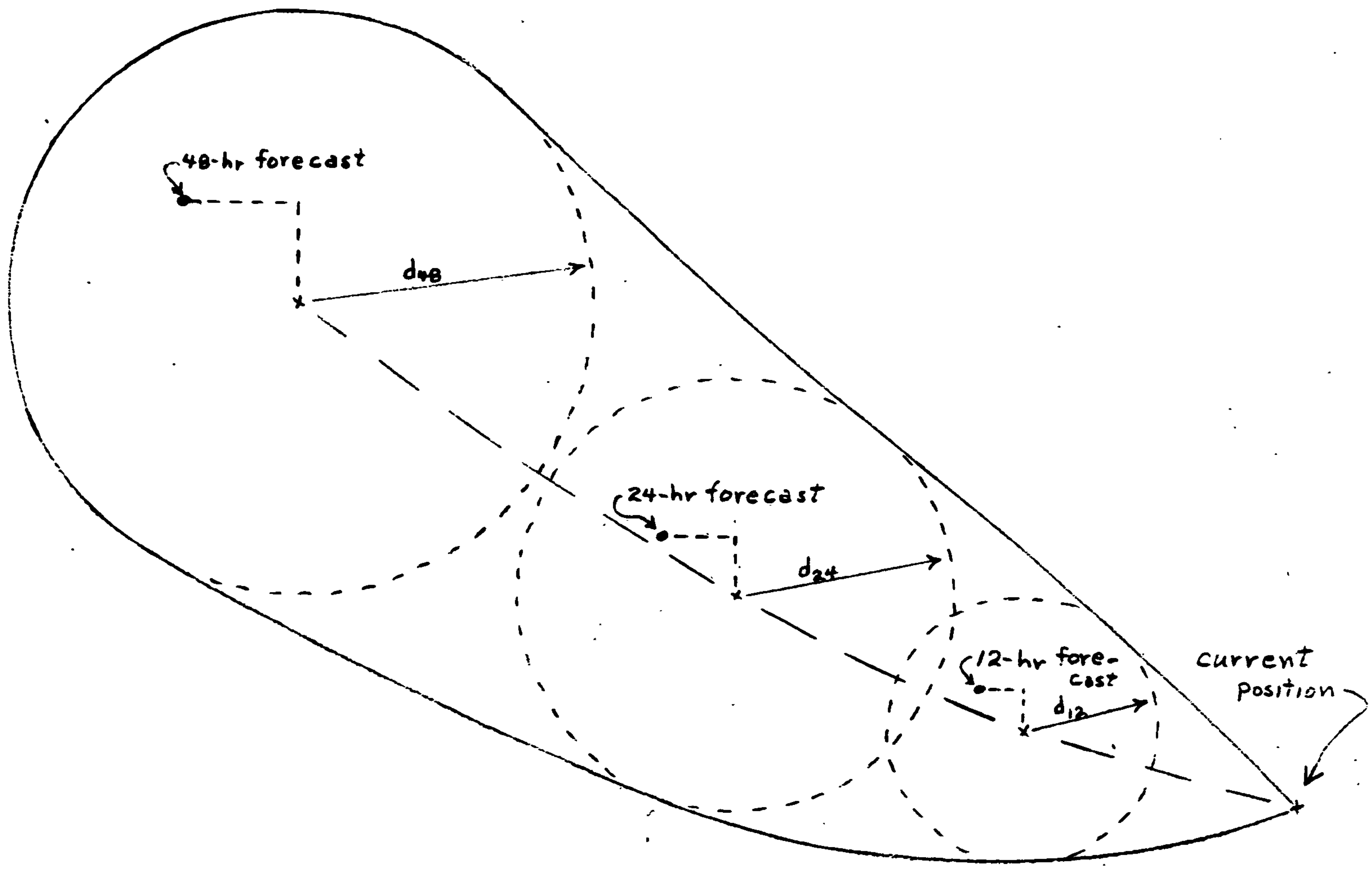



**FIGURE 5**

**Construction of a probability envelope for the path of the storm.**

greatest practical extent. The hurricane "conditions" specified by the usual hurricane plan amount to notifications of the time remaining before the storm is expected to arrive and do not directly refer to states of preparedness. For example, Condition 4 is set to notify the base personnel that a hurricane is approaching; Condition 3 is set whenever hurricane-force* winds are expected to arrive within 48 hours (the bulk of the storm preparations are supposed to be completed while in this condition); Condition 2 is set whenever hurricane-force* winds are forecasted to be 24 hours away; and Condition 1 is set whenever the forecast is for 12 hours.

I would like to propose that consideration be given to the desirability of creating a hurricane plan which consists of a set of states of preparedness with each state representing a different degree of protection. For example, State 3, or Condition 3, if one wants to keep the present terminology, could represent protection against winds of less than 40 knots, State 2 protection against winds of less than 50 knots, and State 1 protection from winds of 50 knots or more.

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*At AFMTC 50 knot winds are used for this criterion rather than hurricane (64 knots or more) winds.

There are several possible advantages for such a scheme. For example, it would provide needed protection from less than hurricane-force winds without wasting money and effort in over-protection. Also, since closure of the base would be gradual, and only as necessary, this scheme should result in less interference with operations.

The development of a hurricane plan with the above feature would require the determination of the appropriate number of preparedness states, and their associated lead times, to include in the plan. To do this properly it will be necessary to make a detailed survey of the requirements for each facility. For example, we need to know for each facility:

(1) What is the maximum wind speed the facility can safely endure without having to take any precautionary measures?

(2) What measures are required to protect the facility from winds of various magnitudes?

(3) What will be the loss in effectiveness for various states of storm preparedness?

(4) How much lead time will be required to go from one state of preparedness to the next?

A proposal on how to obtain answers to these questions and how to use them effectively for selecting the states of preparedness to incorporate in the hurricane plan is presented as Appendix B. An example of the hurricane plan which might result from the procedures described in this appendix is shown in Table 2.

TABLE 2

SAMPLE HURRICANE PLAN

| State of Preparedness | Sustained Wind Speeds (kts) | Lead Time (hrs) | Accumulative Loss in Effectiveness (%) |
|---|---|---|---|
| 4 (normal) | 0 - 30 | 0 | 0 |
| 3 | 30 - 40 | 12 | 30 |
| 2 | 40 - 50 | 24 | 80 |
| 1 | 50 - above | 12 | 100 |

There are a couple of details associated with Table 2 which should, perhaps, be discussed here. First, the wind speeds specified in the plan are sustained surface wind speeds. This does not mean that we are ignoring gusts or increases in wind speed with height. As explained in Appendix B allowances in storm preparations must be made for these phenomena. The relationships between expected gusts and sustained wind speeds and between winds at various heights and those at the surface are discussed in this appendix. Secondly, the lead times shown in Table 2 represent the upper 95% confidence bounds on the times actually needed to complete the required preparations. That is, the probability is 0.95 that the preparations can be completed within the times shown. The procedures for establishing these bounds are described in Appendix B.

6. Critical Probabilities

After a set of states of preparedness for the hurricane plan has been decided upon (e.g., Table 2), the next step would be to obtain some cost estimates. These estimates would serve two purposes: (1) to provide a cost basis for deciding if the proposed plan should be adopted, and (2) to provide means for answering the question, "how large should the critical probabilities be?" A simple comparison of the costs involved in setting the various states of preparedness and the costs of setting State 1 from scratch should give some indication of the economic gain or loss to expect from adopting the proposed plan. The ratio of the buttoning-unbuttoning cost to the anticipated repair cost if caught underprepared can be considered as a reasonable first-order approximation to a proper size for the critical probability. (Actually, it is proposed that the upper 95% confidence bounds on these costs be used for computing this ratio.)

Details on the obtaining of cost estimates and the computing of reference, or base, values for the critical probabilities are contained in Appendix C. However, to be more specific here about the ratios desired, let us consider that $C_i$ represents the upper 95% confidence bound on the total buttoning-unbuttoning cost for setting state i when already at state i + 1 and that $R_i$ represents the upper 95% confidence bound on the total anticipated repair cost if winds of state i should occur while prepared for winds of state i + 1. The desired ratios for state i are

(3) $$p_{ri} = C_i/R_i,$$

and

(4) $$p'_{ri} = \frac{\sum_{k=1}^{i} C_k}{\sum_{k=1}^{i} R_k}$$

The use of equations (3) and (4) are illustrated by Table 3 where a hypothetical set of total costs for each state of preparedness are shown. Why we need two critical probabilities for each state will be explained later.

TABLE 3

SUMMARY OF COST ESTIMATES AND THE RESULTING CRITICAL PROBABILITIES (Hypothetical)

| State of Preparedness | Buttoning-Unbuttoning* (thousands$) | Anticipated Repair Cost* (thousands$) | Critical Probability Reference Values | |
|---|---|---|---|---|
| $i$ | $C_i$ | $R_i$ | $p_{ri}$ | $p'_{ri}$ |
| 3 | 40 | 100 | .400 | .183 |
| 2 | 50 | 300 | .167 | .140 |
| 1 | 20 | 200 | .100 | .100 |

*Values shown represent the upper 95% confidence bound on the actual costs.

7. Decision-making Mechanism

Table 4 contains a sample set of hurricane-plan parameters*. These will be used for illustrating the decision-making mechanism. The procedures can best be illustrated by an example.

*The critical probabilities of Table 4 were deliberately chosen to be different from the reference values of Table 3 in order to reflect the Commander's use of his prerogative to adjust these values to meet a particular situation.

TABLE 4

HURRICANE-PLAN PARAMETERS (SAMPLE)

| State of Preparedness | Sustained Wind Speed (kts) | Lead Time Required (hrs) | Remaining Lead Time (hrs) | Critical Probabilities $p_{ci}$ | $p'_{ci}$ |
|---|---|---|---|---|---|
| 3 | 30-40 | 12 | 48 | .300 | .150 |
| 2 | 40-50 | 24 | 36 | .200 | .100 |
| 1 | 50- | 12 | 12 | .050 | .050 |

Suppose we are in the normal, or unprepared, state of preparedness. To determine if State 3 should be set, we test for the occurrence of 30-knot winds within 48 hours. The wind-speed isogram from the 48-hour forecast is drawn to scale, rotated 180°, and placed over Cape Canaveral, for example, as in Figure 2 b. The 48-hour prognosticated position is located and adjusted for bias. From the adjusted position the closest and farthest distances to the rotated 30-knot isotach are measured. These distances are used as described in section 4 a for computing the probability that 30-knot winds will occur at Cape Canaveral within 48 hours. See equation (2). If this probability exceeds or equals 0.300 (i.e., $p_{c3}$), State 3 should be set. If it does not, then a second probability calculation and comparison is necessary before deciding that it is not necessary to set State 3.

The second probability calculation is made in the same manner as the first except that the rotated isotach corresponding to State 1 instead of State 3 is used. Thus, we test for the occurrence of <u>50-knot</u> winds within 48 hours. The resulting probability is then compared with <u>0.150</u> (i.e., $p'_{c3}$). If it exceeds or equals this amount, State 3 should be set. If it does not, then it is not necessary to set State 3 at this time.

The procedures for deciding if States 2 and 1 should be set are similar to the above. However, each state requires the use of a different isotach and a different forecast period*. Also, the critical probabilities are different for each state.

The reason that it is necessary to make two probability calculations and comparisons is because neither will suffice alone. For example, if we depended upon the first one alone, it is quite conceivable that the situation could occur where the called-for state of preparedness changed from, say, 3 to 1 within a comparatively few hours and we would be caught without sufficient lead time to do so. Therefore, the second one is provided to insure that there will always be sufficient lead time available for setting State 1.

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*It should be noted that our example requires a 36-hour prognosticated position for State 2. Since the Weather Bureau does not make 36-hour forecasts, it would be necessary to make certain interpolations to obtain the required information. This sort of thing is to be expected.

On the other hand the second probability calculation and comparison, which is based on State 1 winds, would not provide assurance that we would always be properly prepared for winds of intermediate force. This is what the first probability calculation and comparison does.

## APPENDIX A. STATISTICAL ANALYSIS OF PROGNOSTICATION ERRORS

Positioning and prognostication data on all tropical storms and hurricanes* occurring in the North Atlantic and likely to present a threat to Florida were obtained for the years 1955, 1956, 1958, and 1959 from the Air Force Hurricane Liaison Officer's Report for 1959. There were no such storms reported for 1957. In addition to the above, similar data were already on hand from hurricane "Donna" of 1960.

A total of 30 storms was included in the above collection. However, some of these were short lived and others did not remain long within the area of interest. Thus, the number of pairs of data points contributed by some storms was small. (A pair of data points consists of a prognosticated position and the corresponding actual position.) Altogether there were 381 pairs of data points from the 12-hour forecasts, 330 pairs from the 24-hour forecasts, and 14 pairs from the 48-hour forecasts. This latter set of points came from hurricane Donna alone as there were no 48-hour prognostications published prior to 1960.

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*A "disturbance" is classified as a tropical storm when the maximum surface winds are from 34 to 63 kts and as a hurricane when they are 64 kts or over.

In order to investigate the possibility that the accuracy of the prognostications varied with storm location, the general area of interest was subdivided into four sub-areas. These divisions are indicated in Figure 1A. In general, area A consisted of the Caribbean Sea, area B the Gulf of Mexico over to $81^{\circ}$ W longitude, area C the Atlantic Ocean between $81^{\circ}$ W and $70^{\circ}$ W longitudes and between $20^{\circ}$ N and $30^{\circ}$ N latitude, and area D the Atlantic Ocean between $70^{\circ}$ W and $50^{\circ}$ W longitude and between $20^{\circ}$ and $30^{\circ}$ N latitudes. No data were considered that fell outside of these areas. The sample sizes by area and year are shown in Table 1A.

It was not possible to investigate for differences between prognostication methods because, according to the information received at AFMTC, the published prognostications normally do not come from any one method or from any one combination of methods. Instead, during a given storm several methods are used to obtain independent results and then these results are weighed and combined in whatever manner seems best in the judgment of the prognosticator.

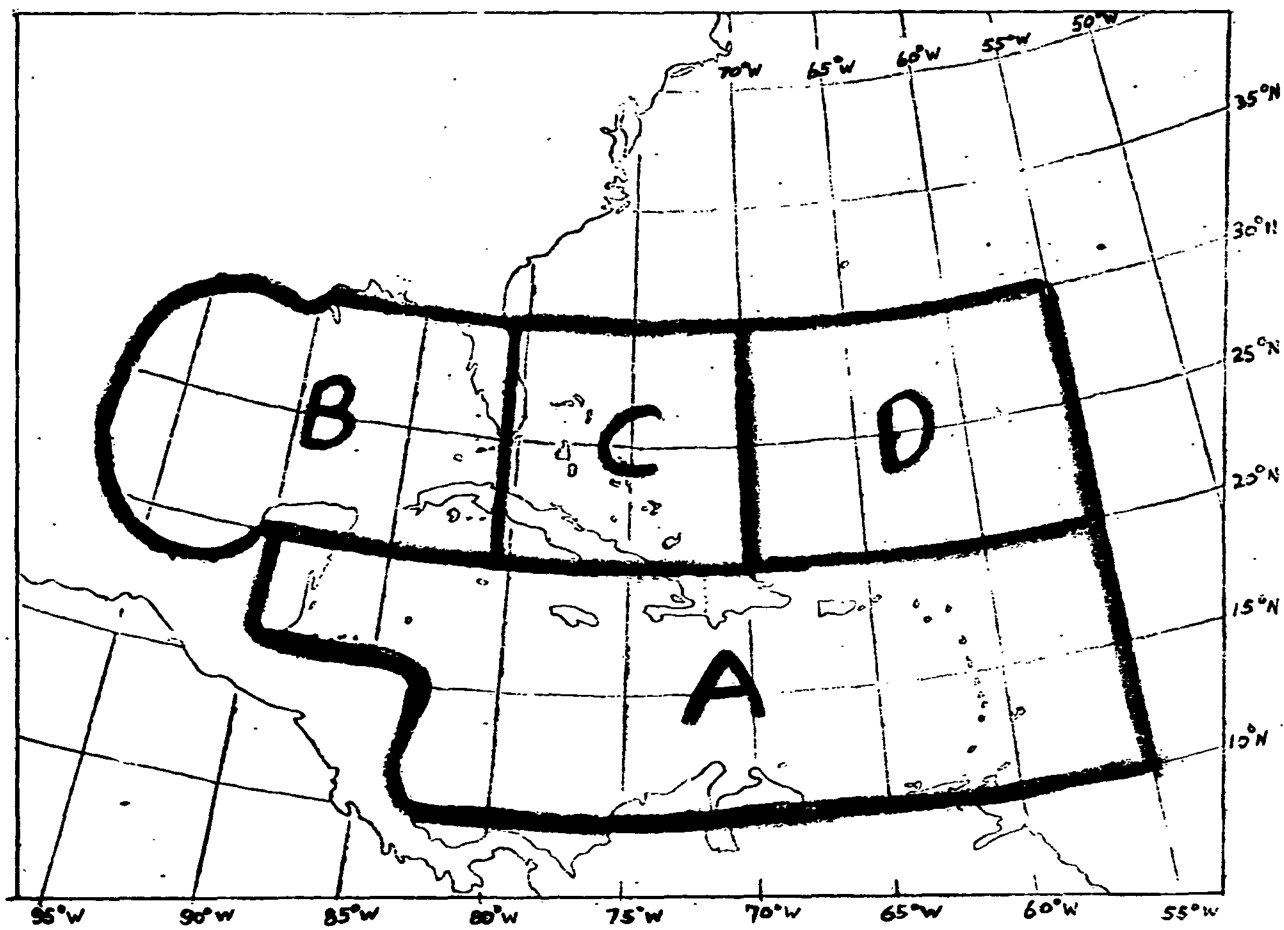



**FIGURE 1A**

Division of area of interest into subareas

## TABLE 1A

## SAMPLE SIZE BY AREA AND YEAR

| Forecast Period | Area | 1955 | 1956 | 1958 | 1959 | 1960 | Total |
|---|---|---|---|---|---|---|---|
| 12-hour | A | 39 | 8 | 19 | 5 | 9 | 80 |
| " | B | 24 | 7 | 15 | 24 | 5 | 75 |
| " | C | 26 | 17 | 35 | 28 | 14 | 120 |
| " | D | 48 | 6 | 38 | 10 | 4 | 106 |
| 24-hour | A | 34 | 6 | 12 | 3 | 9 | 64 |
| " | B | 20 | 5 | 15 | 13 | 5 | 58 |
| " | C | 23 | 15 | 31 | 28 | 13 | 110 |
| " | D | 44 | 4 | 38 | 8 | 4 | 98 |
| 48-hour | A | - | - | - | - | 3 | 3 |
| " | B | - | - | - | - | 3 | 3 |
| " | C | - | - | - | - | 6 | 6 |
| " | D | - | - | - | - | 2 | 2 |

To obtain a measure of the accuracy with which the movement of tropical storms and hurricanes could be predicted, each storm position was compared with its corresponding prognosticated position. The displacement between each pair of positions was resolved into east-west and north-south components for analysis purposes. The formulas used were:

$$\text{east-west component} = x = 60\,(\lambda_2 - \lambda_1)\cos\frac{L_2 + L_1}{2},$$

$$\text{north-south component} = y = 60\,(L_2 - L_1),$$

where $(L_1, \lambda_1)$ represent the latitude and longitude, respectively, of the prognosticated position and $(L_2, \lambda_2)$ the latitude and longitude of the actual position. (The factor of 60 was provided to obtain units of nautical miles with the latitudes and longitudes being expressed in degrees.) Since storm positions are usually given to the nearest tenth of a degree and the separation between positions is normally a matter of a few degrees, these formulas should be sufficiently accurate.

The individual prognostication errors were not tabulated for inclusion herein. However, the average values and the standard deviations for the various areas and years are presented in Tables 2A and 3A for the 12-hour and the 24-hour forecasts, respectively. The coefficients of correlation

TABLE 2A. SUMMARY OF THE PROGNOSTICATION ERRORS FOR THE 12-HOUR FORECASTS

| Area | Year | Sample Size n | East-West Component (x) Average* (n.m.) | East-West Component (x) Standard Deviation (n.m.) | North-South Component (y) Average* (n.m.) | North-South Component (y) Standard Deviation (n.m.) | Coefficient of Correlation |
|---|---|---|---|---|---|---|---|
| A | 1955 | 39 | 10.3 | 50.3 | -2.3 | 38.1 | -.116 |
| A | 1956 | 8 | 2.1 | 24.8 | 17.2 | 27.3 | .020 |
| A | 1958 | 19 | -31.6 | 68.9 | -12.9 | 56.7 | .591 ## |
| A | 1959 | 5 | 101.0 | 74.0 | 34.8 | 56.2 | .020 |
| A | 1960 | 9 | -8.1 | 39.5 | 5.3 | 26.2 | .020 |
| B | 1955 | 24 | -11.2 | 42.2 | -8.5 | 53.8 | .020 |
| B | 1956 | 7 | -33.2 | 50.5 | -20.6 | 71.6 | -.634 |
| B | 1958 | 15 | 8.1 | 45.3 | -10.0 | 48.8 | .723 |
| B | 1959 | 24 | -18.7 | 44.9 | -30.8 | 54.8 | -.516 # |
| B | 1960 | 5 | -20.2 | 34.4 | 19.2 | 16.1 | -.634 |
| C | 1955 | 26 | -1.8 | 42.8 | -7.8 | 45.7 | .065 |
| C | 1956 | 17 | -6.0 | 64.0 | -26.1 | 56.4 | -.685 ## |
| C | 1958 | 35 | -17.0 | 69.8 | 2.4 | 87.0 | -.283 |
| C | 1959 | 28 | -24.0 | 87.8 | -16.5 | 37.4 | .141 |
| C | 1960 | 14 | -9.0 | 30.9 | -11.6 | 29.6 | -.550 |
| D | 1955 | 48 | -6.0 | 75.5 | 1.4 | 57.4 | .011 |
| D | 1956 | 6 | -11.8 | 96.6 | 58.0 | 234.9 | -.731 |
| D | 1958 | 38 | -5.5 | 62.6 | -5.2 | 63.8 | -.301 |
| D | 1959 | 10 | -31.1 | 55.6 | 32.4 | 60.9 | -.731 ## |
| D | 1960 | 4 | -23.8 | 17.4 | -4.5 | 13.1 | -.731 |
| | | 381 | | | | | |

* A negative x signifies that the prognosticated position of the storm was west of the true position and a negative y signifies that the prognosticated position was north of the true position.

\# Significantly different from zero at the .05 level.

\## Significantly different from zero at the .01 level.

TABLE 3A SUMMARY OF THE PROGNOSTICATION ERRORS FOR THE 24-HOUR FORECASTS

| Area | Year | Sample Size n | East-West Component (x) Average* (n.m.) | East-West Component (x) Standard Deviation (n.m.) | North-South Component (y) Average* (n.m.) | North-South Component (y) Standard Deviation (n.m.) | Coefficient of Correlation |
|---|---|---|---|---|---|---|---|
| A | 1955 | 34 | 24.5 | 84.5 | -14.1 | 66.2 | -.145 |
| A | 1956 | 6 | -6.8 | 27.5 | 47.0 | 55.2 | .514 |
| A | 1958 | 12 | -5.3 | 129.3 | -17.0 | 53.3 | .002 |
| A | 1959 | 3 | 270.5 | 83.4 | 98.0 | 6.9 | .514 |
| A | 1960 | 9 | 1.0 | 67.1 | 0 | 33.7 | .514 |
| B | 1955 | 20 | -27.4 | 104.0 | -4.5 | 78.3 | -.129 |
| B | 1956 | 5 | -43.0 | 67.7 | -91.2 | 102.7 | -.427 |
| B | 1958 | 15 | 5.8 | 86.1 | -15.6 | 67.8 | .695 ## |
| B | 1959 | 13 | -26.4 | 33.8 | -126.5 | 72.2 | .332 |
| B | 1960 | 5 | -55.8 | 36.6 | 42.0 | 37.2 | -.427 |
| C | 1955 | 23 | 2.5 | 65.5 | -17.5 | 74.5 | -.096 |
| C | 1956 | 15 | -37.9 | 84.2 | -41.2 | 91.4 | -.378 |
| C | 1958 | 31 | -23.2 | 111.1 | 1.2 | 129.6 | -.416 # |
| C | 1959 | 28 | -56.9 | 131.9 | -61.9 | 68.0 | .272 |
| C | 1960 | 13 | 0.5 | 40.7 | -48.0 | 46.0 | -.755 ## |
| D | 1955 | 44 | -12.9 | 144.3 | 0.3 | 106.9 | .146 |
| D | 1956 | 4 | -111.3 | 107.8 | 333.0 | 133.0 | -.324 |
| D | 1958 | 38 | -36.6 | 92.4 | 12.0 | 98.1 | -.050 |
| D | 1959 | 8 | -95.8 | 145.4 | 72.0 | 104.6 | -.324 |
| D | 1960 | 4 | -78.3 | 34.7 | -19.5 | 41.6 | .324 |
| | | 330 | | | | | |

* A negative x signifies that the prognosticated position of the storm was west of the true position and a negative y signified that the prognosticated position was north of the true position.

\# Significantly different from zero at the .05 level.

\## Significantly different from zero at the .01 level.

between x and y are also included in these tables. Since the data for the 48-hour forecast period were so scarce (only 14 pairs of data points), it was decided to treat these data as one set rather than to divide them among the various areas. The averages, standard deviations, and the coefficient of correlation for this one set are presented in Table 4A.

As can be seen in the above tables the coefficients of correlation were for the most part not significantly different from zero at the .05 level. There were only a few instances where the test (Student-t) showed significance.* Therefore, we shall adopt the hypothesis that the error components are uncorrelated.

To obtain an insight into the probability distributions of the prognostication errors, the frequency distribution of the computed errors were determined. These are presented in Figures 2A and 3A for the 12-hour and 24-hour forecasts, respectively. Here the frequency of occurrence is plotted against the midpoint of the interval.

---

*Significantly different from zero at the $\alpha$-level means that the probability is $\alpha$, or less, that a random sample of size n from a bivariate population with zero correlation would have a correlation coefficient as large (in absolute value) as that obtained.

TABLE 4A

SUMMARY OF THE PROGNOSTICATION ERRORS FOR THE 48-HOUR FORECASTS

| Year | Sample Size n | East-West Component (x) Average (n.m.) | East-West Component (x) Standard Deviation (n.m.) | North-South Component (y) Average (n.m.) | North-South Component (y) Standard Deviation (n.m.) | Coefficient of Correlation |
|---|---|---|---|---|---|---|
| 1960 | 14 | -20.3 | 124 | -76.7 | 114 | .538 # |

# Significantly different from zero at the .05 level.

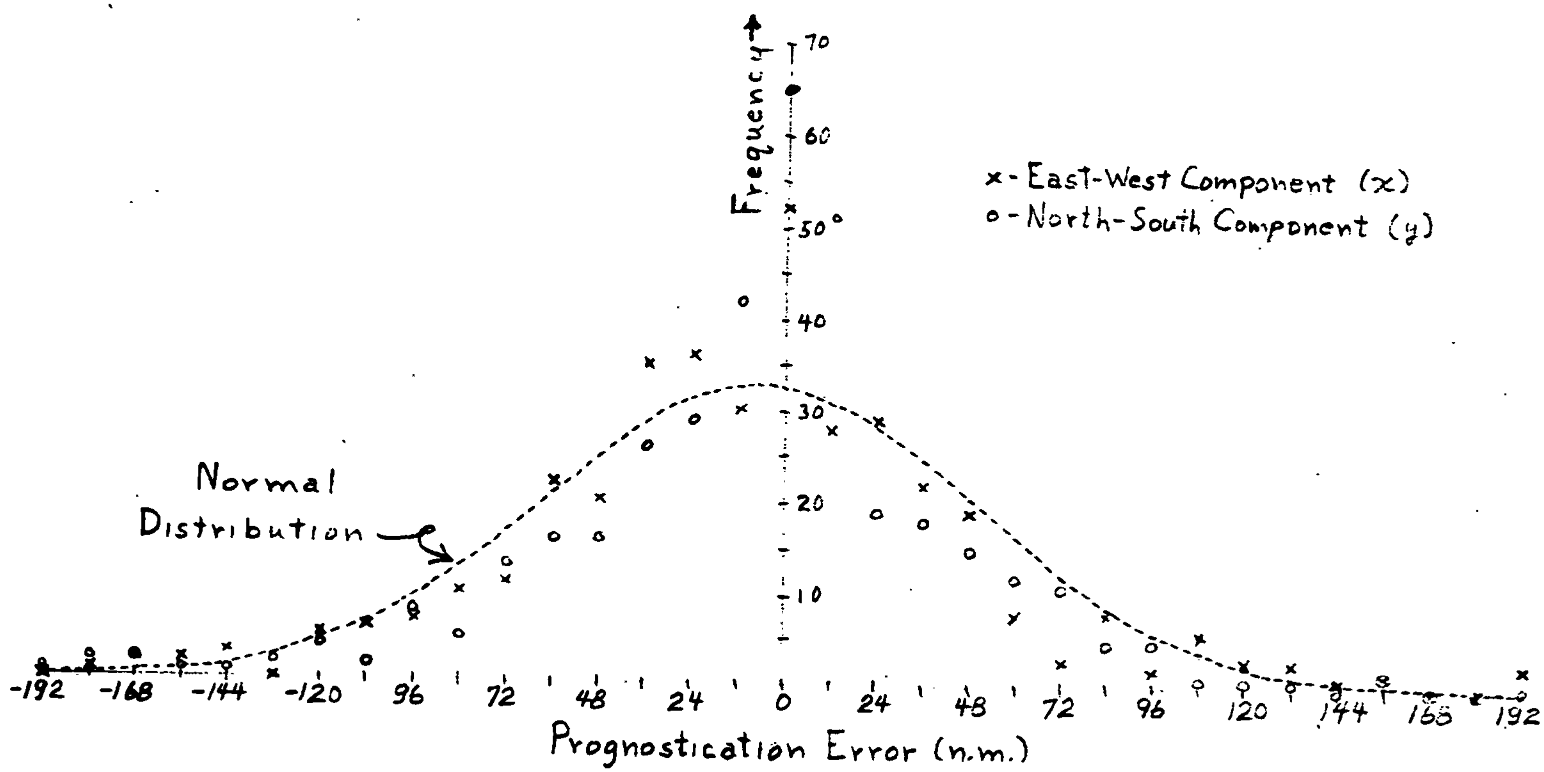



FIGURE 2A

Frequency distributions of prognostication errors for the 12-hour forecasts.

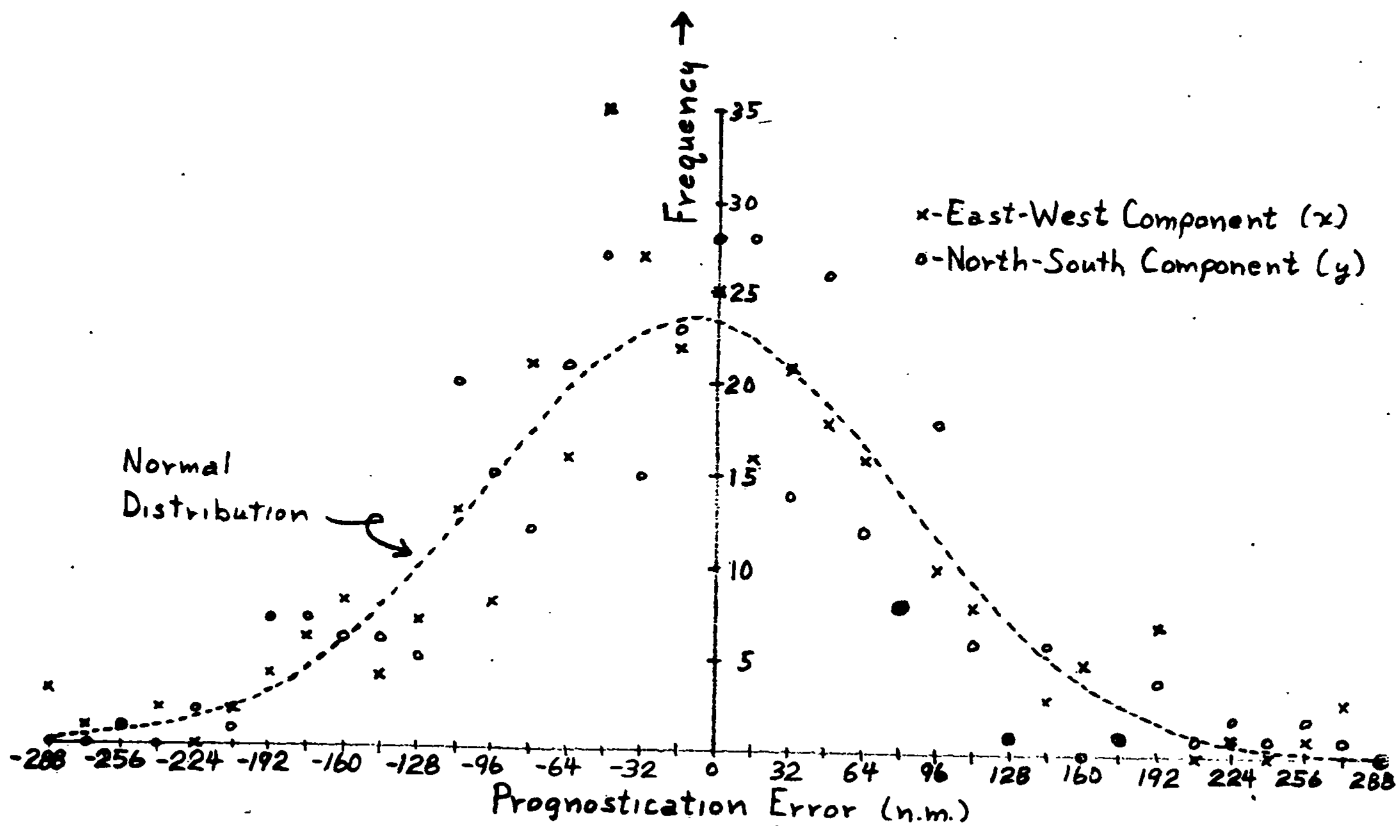



**FIGURE 3A**

Frequency distributions of prognostication errors for the 24-hour forecasts.

The normal distribution was fitted to the data for each forecast period. As can be observed, the frequency distributions of the prognostication errors were approximately normal, although somewhat peaked in the center. Accordingly, it should be reasonably safe to assume a bivariate normal probability distribution for the prognostication errors.

Under the assumptions of a bivariate normal distribution and zero correlation the equation for an "equiprobability" ellipse for the prognostication errors would be given by

$$c^2 = \frac{(x-\bar{x})^2}{\sigma_x^2} + \frac{(y-\bar{y})^2}{\sigma_y^2} ,$$

where

$c$ = a constant,

$\bar{x}$ = the average value of x,

$\bar{y}$ = the average value of y.

$\sigma_x$ = the standard deviation of x, and

$\sigma_y$ = the standard deviation of y.

In case $\sigma_x = \sigma_y = \sigma$, the probability ellipse reduces to a circle with radius $c\sigma$. The probability, p, that a pair of prognostication errors, (x, y), chosen at random will fall within the ellipse (or circle) is determined by

$$p = 1-e^{-c^2/2} \quad .$$

If we consider the past to be indicative of the future, the above results can be used for establishing ellipses, or possibly circles, around future prognosticated positions, but centered $\bar{x}$, $\bar{y}$ units away from this position, which will with probability p contain the actual position of the storm at the end of the forecast period. It remains for us to determine the best estimates of the distribution parameters, i.e., $\bar{x}$, $\bar{y}$, $\sigma_x^2$ , and $\sigma_y^2$ .

Before attempting to estimate the distribution parameters, let us first investigate for possible differences between areas and between years in the matter of accuracy of prognostication. For this purpose the technique of the analysis of variance will be used.*

---

*There were a few extreme error values that appeared to be inconsistent with the rest of the data. Since it was feared they might exert an undue influence on the statistical analyses to follow, it was decided to simply omit them. There were four x values and five y values from the 12-hour prognostications and six x values and three y values from the 24-hour prognostications so omitted.

The results of the analysis of variance on the prognostication errors from the 12-hour forecasts are presented in Tables 5A and 6A for the x and y components, respectively. Here it can be seen that neither the differences between areas nor the differences between years were significant at the .05 level.*

---

* Significant at the $\alpha$-level would mean that the computed F value equaled or exceeded the theoretical $F_\alpha$ value. The $F_\alpha$ value represents how large F can be expected to become $100\alpha$ % of the time simply because of chance variation in the data.

TABLE 5A

RESULTS OF THE ANALYSIS OF VARIANCE ON PROGNOSTICATION ERRORS FROM THE 12-HOUR FORECASTS (east-west component)

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | F | $F_{.05}$ |
|---|---|---|---|---|---|
| Total | 1,265,099 | 376 | | | |
| Areas | 12,696 | 3 | 4232 | 1.25 | 2.62 |
| Years | 4,123 | 4 | 1031 | .30 | 2.39 |
| Residual | 1,248,280 | 369 | 3383 | | |

TABLE 6A

RESULTS OF THE ANALYSIS OF VARIANCE ON PROGNOSTICATION ERRORS FROM THE 12-HOUR FORECASTS (north-south component)

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | F | $F_{.05}$ |
|---|---|---|---|---|---|
| Total | 1,068,345 | 375 | | | |
| Areas | 11,637 | 3 | 3879 | 1.36 | 2.62 |
| Years | 10,441 | 4 | 2610 | .92 | 2.39 |
| Residual | 1,046,267 | 368 | 2843 | | |

The best estimate of the variance of either x or y is the residual mean square from the respective analysis of variance. However, a statistical test showed that these variances did not differ significantly at the .05 level from each other.* Accordingly, the variances were pooled and we obtained

$$\sigma_x^2 \quad = \quad \sigma_y^2 \quad = \quad 3113 \text{ (n.m.)}^2$$

and, hence,

$$\sigma_x \quad = \sigma_y \quad = \quad 55.8 \text{ n.m.}$$

The computed averages were -7.4 and -7.1 nautical miles for x and y, respectively. Again, a statistical test showed that these values did not differ significantly from each other.** However, they both differed significantly from zero.** Accordingly, we obtained

$$\bar{x} = \bar{y} = \; -7.2 \text{ n.m.}$$

---

* $F = \dfrac{\sigma_x^2}{\sigma_y^2} = 1.19$, but $F_{.05} = 1.22$.

** $t$ (for $\bar{x} = \bar{y}$) = 1.57, $t$ (for $\bar{x} = 0$) = 2.48,
$t$ (for $\bar{y} = 0$) = 2.58 with $t_{.05} = 1.96$.

The results of the analyses of variance on the prognostication errors from the 24-hour forecasts are presented in Tables 7A and 8A for the x and y components, respectively. Here, for both x and y, it can be seen that the differences between areas were significant at the .01 level and the differences between years were significant at the .05 level. Investigations indicated that these effects were attributable to the 1959 data. Indeed, when analyses of variance were conducted on the remaining data, the results showed that none of the differences were significant at the .05 level. See Tables 9A and 10A.

Why the positioning data for 1959 from the 24-hour forecasts should be different from that for the other years is not clear. The details on how these prognostications were made, or on how they may have differed from those for the other years, were not available. It was decided to omit the 1959 data and to consider the data from the other years as being sufficient and proper for estimating the distribution parameters for the 24-hour prognostication errors.

TABLE 7A

RESULTS OF THE ANALYSIS OF VARIANCE ON PROGNOSTICATION ERRORS FROM THE 24-HOUR FORECASTS (east-west component)

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | F | $F_{.05}$ | $F_{.01}$ |
|---|---|---|---|---|---|---|
| Total | 3,008,330 | 323 | | | | |
| Areas | 103,282 | 3 | 34,427 | 3.87 | 2.63 | 3.85 |
| Years | 91,935 | 4 | 22,984 | 2.58 | 2.40 | 3.38 |
| Residual | 2,813,113 | 316 | 8,902 | | | |

TABLE 8A

RESULTS OF THE ANALYSIS OF VARIANCE ON PROGNOSTICATION ERRORS FROM THE 24-HOUR FORECASTS (north-south component).

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | F | $F_{.05}$ | $F_{.01}$ |
|---|---|---|---|---|---|---|
| Total | 2,805,071 | 326 | | | | |
| Areas | 135,779 | 3 | 45,260 | 5.59 | 2.63 | 3.85 |
| Years | 88,549 | 4 | 22,137 | 2.74 | 2.40 | 3.38 |
| Residual | 2,580,743 | 319 | 8,090 | | | |

TABLE 9A

RESULTS OF THE ANALYSIS OF VARIANCE ON PROGNOSTICATION ERRORS FROM THE 24-HOUR FORECASTS WITH THE 1959 DATA OMITTED (east-west component).

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | F | $F_{.05}$ |
|---|---|---|---|---|---|
| Total | 2,309,120 | 273 | | | |
| Areas | 52,170 | 3 | 17,390 | 2.12 | 2.64 |
| Years | 62,815 | 3 | 20,938 | 2.55 | 2.64 |
| Residual | 2,194,135 | 267 | 8,218 | | |

TABLE 10A

RESULTS OF THE ANALYSIS OF VARIANCE ON PROGNOSTICATION ERRORS FROM THE 24-HOUR FORECASTS WITH THE 1959 DATA OMITTED (north-south component)

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | F | $F_{.05}$ |
|---|---|---|---|---|---|
| Total | 2,203,548 | 274 | | | |
| Areas | 29,457 | 3 | 9,819 | 1.22 | 2.64 |
| Years | 15,786 | 3 | 5,262 | .65 | 2.64 |
| Residual | 2,158,305 | 268 | 8,053 | | |

The variances of x and y for the 24-hour forecasts did not differ significantly at the .05 level from each other.* Therefore, the variances were pooled and we obtained

Thus,

$$\sigma_x^2 = \sigma_y^2 = 8135 \text{ (n.m.)}^2 \; .$$

$$\sigma_x \doteq \sigma_y = 90.2 \text{ n.m.}$$

The computed averages were -12.7 and -7.4 nautical miles for x and y, respectively. These values did not differ significantly from one another; however, the average x value differed significantly from zero whereas the average y value did not.** It was decided that we would be less likely to be in error if we accepted the hypothesis that $\bar{x} = \bar{y} \neq 0$.

$$\bar{x} = \bar{y} = -10.0 \text{ n.m.}$$

---

* $F = \dfrac{\sigma_x^2}{\sigma_y^2} = 1.02$, but $F_{.05} = 1.26$.

** t(for $\bar{x} = \bar{y}$) = 0.68, t(for $\bar{x} = 0$) = 2.31, t(for $\bar{y} = 0$) = 1.37, while $t_{.05} = 1.96$.

The prognostication errors from the 48-hour forecasts were not segregated by areas since the sample size was so small for each area. Naturally, then, no test for differences between areas could be made. Also, no test for differences between years could be made since there was only one year involved.

The averages and the standard deviations of the prognostication errors for the 48-hour forecasts can be seen in Table 4A. Statistical tests showed that the respective variances and the respective averages did not differ significantly at the .05 level.* However, $\bar{y}$ differed significantly from zero whereas $\bar{x}$ did not.** It was decided to accept the hypothesis that $\bar{x} = \bar{y} \neq 0$. When we pooled the variances we obtained

$$\sigma_x^2 = \sigma_y^2 = 14{,}152 \text{ (n.m.)}2$$

and hence,

$$\sigma_x = \sigma_y = 118.9 \text{ n.m.}$$

When we pooled the averages we obtained

$$\bar{x} = \bar{y} = -48.5 \text{ n.m.}$$

---

* $F = \dfrac{\sigma_x^2}{\sigma_y^2} = 1.18$, but $F_{.05} = 2.58$; t(for $\bar{x} = \bar{y}$) = 1.25, but $t_{.05} = 2.16$.

** T(for $\bar{y} = 0$) = 2.52, t(for $\bar{x} = 0$) = 0.61, with $t_{.05} = 2.16$.

We have seen that the components of error can be considered as being uncorrelated and bivariate normally distributed. Furthermore, our tests showed that the variances of the error components were not statistically significantly different for any of the forecast periods considered. Accordingly, we can consider that the components are circularly normally distributed. The radius, d, of an equiprobability circle would be determined by

$$d = c\sigma$$

Hence,

$$c = d/\sigma,$$

and the probability, P, that a pair of prognostication errors chosen at random will fall within the equiprobability circle can be written as

$$P = 1 - e^{-\frac{1}{2}(d/\sigma)^2}.$$

The best estimates of the distribution parameters for the prognostication errors are summarized in Table 11A below. It should be noted that a negative $\bar{x}$ means that the center of the equi-probability circle should be placed $\bar{x}$ nautical miles eastward from the prognosticated position and a negative $\bar{y}$ means that the center should be placed $\bar{y}$ miles south of the prognosticated position.

TABLE 11A

BEST ESTIMATES OF THE DISTRIBUTION PARAMETERS.

| Forecast Period | Parameter Estimates | |
|---|---|---|
| 12-hour | $\bar{x} = \bar{y} = -7$ n.m.; | $\sigma_x^2 = \sigma_y^2 = 3{,}113$ (n.m.)$^2$ |
| 24-hour | $\bar{x} = \bar{y} = -10$ n.m.; | $\sigma_x^2 = \sigma_y^2 = 8{,}135$ (n.m.)$^2$ |
| 48-hour | $\bar{x} = \bar{y} = -48$ n.m.; | $\sigma_x^2 = \sigma_y^2 = 14{,}152$ (n.m.)$^2$ |

Since we shall probably be interested in constructing equi-probability circles for various time periods, we should be prepared to interpolate between the particular averages and standard deviations obtained for the 12-, 24-, and 48-hour forecast periods. To aid in this interpolation the necessary curves have been constructed and are presented in Figures 4A and 5A.

It is important to note that additional positioning and prognosticating data from 48-hour forecasts are needed in order that more reliable estimates of the distribution parameters for this period can be made. Furthermore, since the methods and procedures used in prognosticating storm movement will probably change as time passes, it is advisable that statistical analyses of prognostication errors be conducted on a recurring basis in order to verify or modify, as the case may be, the results obtained herein.

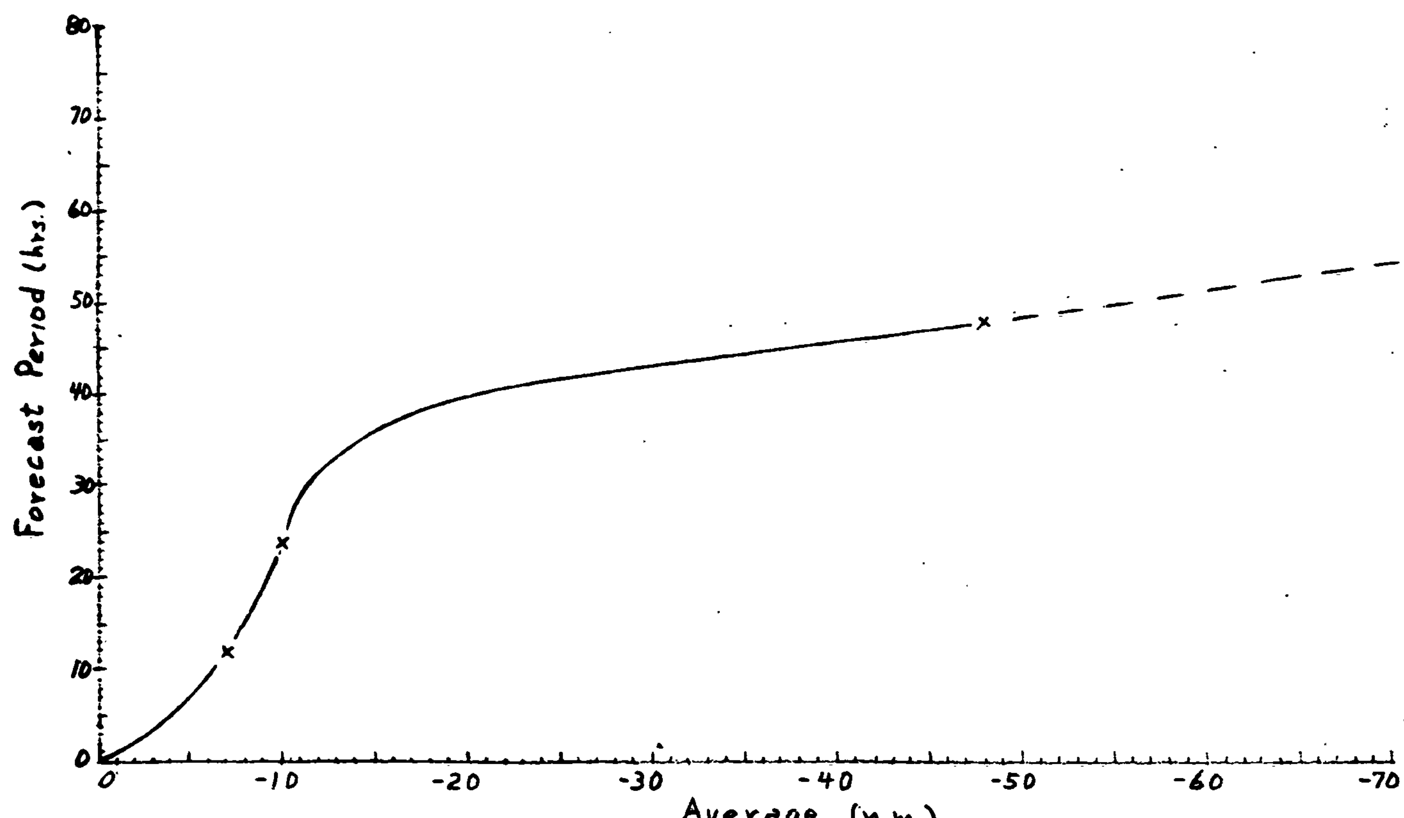
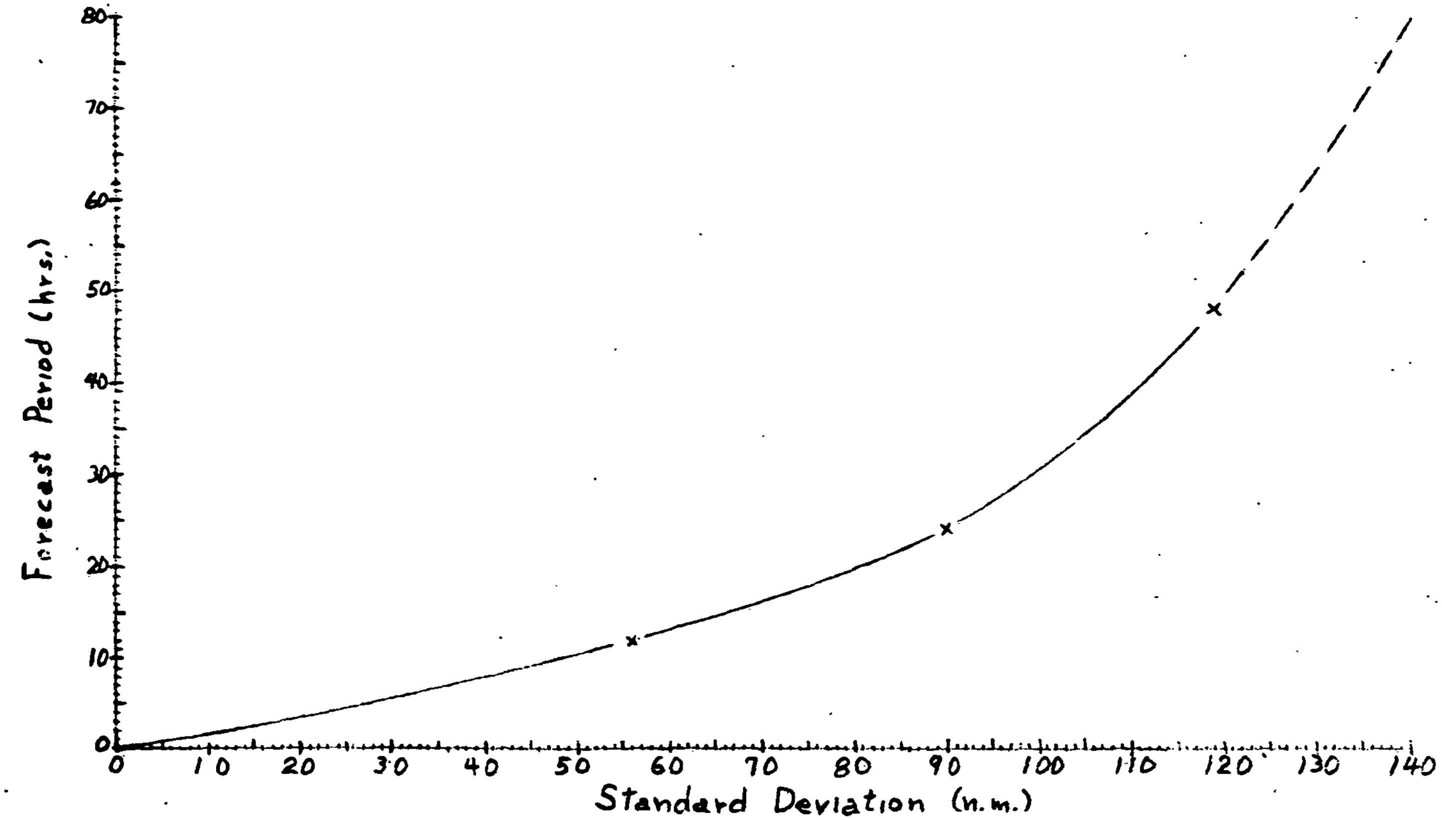



FIGURE 4A

Average Component error as a function of forecast period.




Component error standard deviation as a function of forecast period.

FIGURE 5A.

## APPENDIX B. A PROPOSAL ON HOW TO SELECT STATES OF PREPAREDNESS TO INCLUDE IN A HURRICANE PLAN

In order to decide how many states of preparedness to include in the hurricane plan and how much lead time to provide, it will probably be necessary to conduct an extensive survey of the requirements for each base facility. In particular, it will be necessary to determine the following:

(1) The maximum sustained wind the facility can safely endure without having to take any precautionary measures.

(2) What measures should be taken to protect the facility from sustained winds of various magnitudes.

(3) The loss in effectiveness resulting from the establishment of various states of storm preparedness.

(4) The lead time required to go from one state of preparedness to the next.

A facility survey form was derived for obtaining the above information. This form is presented as enclosure 1. In filling out the form there are several matters that need to be kept in mind. For example, the wind speeds specified are the sustained, or average, surface winds. In deciding what preparations are required for protecting the facility against a specified wind speed, allowances must be made for gusts and for increases in wind speed with height. The relationships between most probable gusts and sustained wind speeds and between wind speeds at various heights and surface wind speeds have been determined empirically for hurricanes and tropical storms.* These relationships are presented as Figures 1B and 2B, respectively.

Another example is that in deciding what the required preparations are, it should be borne in mind that it may be unwise to insist that all storm preparations be conducted on an incremental basis. That is, it may turn out for certain facilities because of excessive costs in time, manpower, and/or resources, or for some other reason, that it would be advisable to prepare immediately for, say, 50-knot winds rather than to plan to prepare for 30-knot winds first, then 40-knot winds if necessary and then 50-knot winds if necessary. However, the "costs" are not the only consideration in deciding whether or not to abandon the step-by-step process. For crucial facilities (i.e., those needed for missile testing) an overriding factor could well be "how much effectiveness is lost in taking one large step compared with the distribution of this loss between steps if smaller steps are taken?"

In any event when it is decided that one large preparedness step should be taken rather than two or more small ones, the required preparations should be listed opposite the first wind speed being protected against. The

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* "Handbook of Geophysics for AF Designers" Geophysics Research Directorate of the AF Cambridge Research Center, 1957.

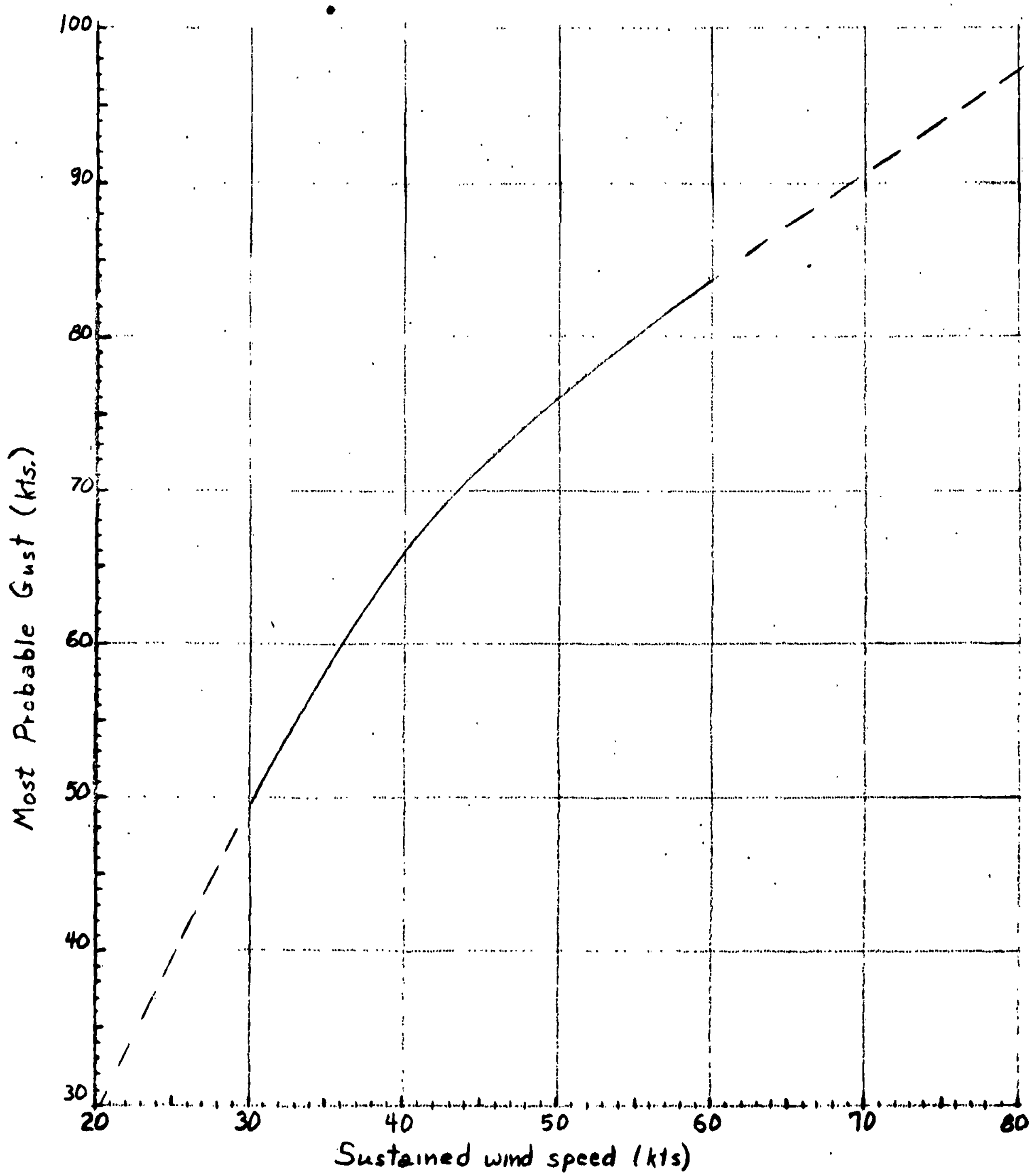


FIGURE 1B

Most probable gust as a function of the
sustained wind speed

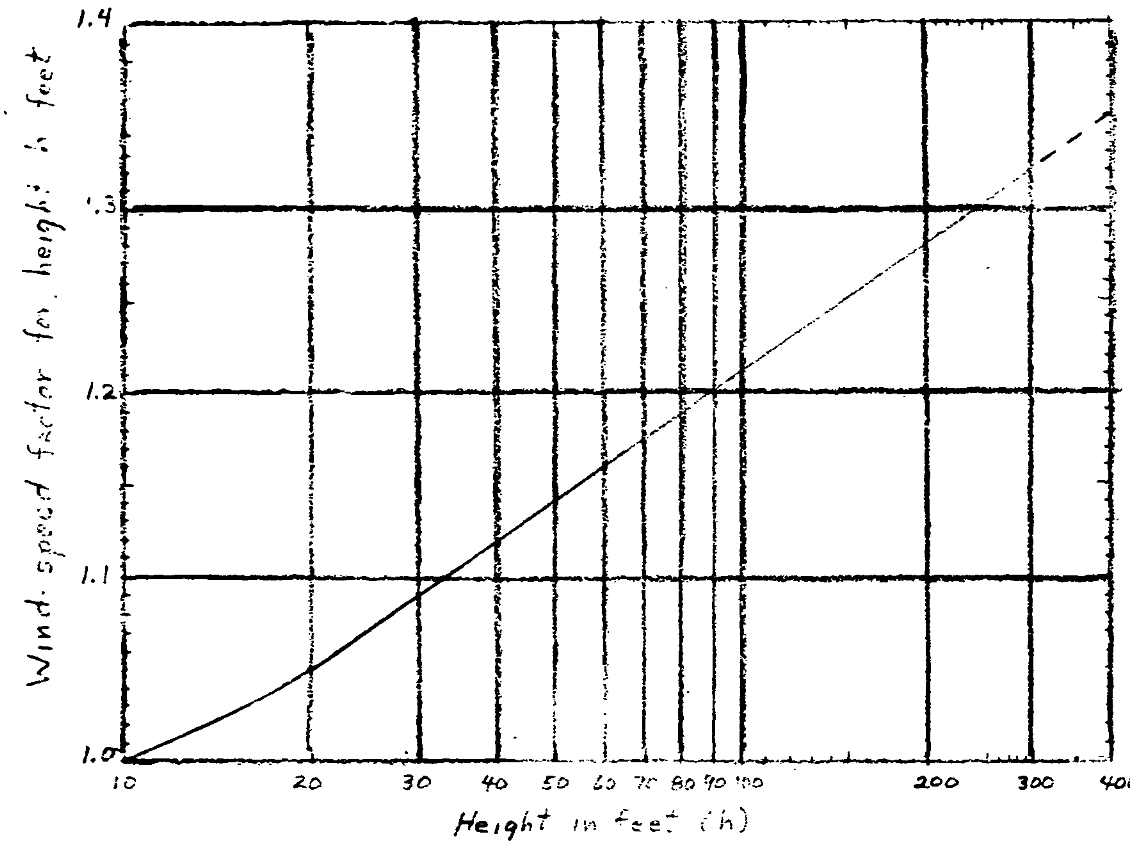


FIGURE 2B

Wind-speed factor versus height above surface (reference height at 10 feet).

lead time shown for this first wind speed should represent the total time needed to complete all the preparations. For subsequent wind speeds only the additional preparations and lead times needed, if any, should be shown.

An "effectiveness lost" column is provided on the survey form for indicating the overall effect that each degree of preparedness has on the operating efficiency of the facility. This information is to be utilized as an aid in deciding what interval of wind speeds to include in each state of preparedness.

The last column on the form is for estimating, in continuous clock hours, the time needed to complete the required preparations. Since these estimates will be subject to considerable variation, it was decided to employ the procedures used in the PEP/PERT Management Control Technique. Accordingly, three time estimates are required for each level of preparedness; namely, the most likely (m), the optimistic (b), and the pessimistic (c).

The three estimated times are defined, rather loosely to be sure, as follows: (a) The most likely time is the best possible estimate of how long it will take to complete the preparations, (b) the optimistic time is the best time within which it could be considered reasonably possible to complete the job, and (c) the pessimistic time is the longest time it should take even if considerably more than the usual number of things go wrong.

It is proposed that the three time estimates be combined (by the coordinating agency) to obtain the upper 95% confidence bound, t, on the required lead time, $\tau$, and that this upper bound should then be used to replace the three estimates. The proposed combining formula is*

(1B) $$t = E(\tau) + 2\sigma_{\tau} ,$$

where

$$E(\tau) = \frac{b+4m+c}{6}$$

and

$$\sigma_{\tau} = \frac{c-b}{6} .$$

---

*It is believed that the variable $\tau$ will be Beta distributed. However, rather than to complicate matters, it was decided that it would be safe to approximate the 95% upper bound on $\tau$ by $E(\tau) + 2\ \sigma_{\tau}$ since the 95% upper bound on a normally distributed variable would be $E\ (\tau) + 1.645\ \sigma_{\tau}$ .

In case two or more facilities are to be "buttoned-up" by the same group of men, it will be necessary to incorporate this fact in the lead-time estimates. The reason for this is that it is intended that one should be able to ascertain how long it will take to prepare the entire center for a given wind speed by simply looking for the longest lead time required by any facility for that wind speed. Thus, it would be misleading if the lead-time estimates appearing on the facility survey form referred to that particular facility alone when said facility was only one in a series of facilities to be buttoned-up by the same work force. To avoid this the lead-time estimates appearing on the forms for such facilities should represent the total time required for the whole series of facilities.

After the survey has been completed it will be the responsibility of some coordinating agency, such as DCS/Operations, to analyze the accumulated data and to initiate the development of a hurricane plan along the lines previously described. Specifically, the agency will have to determine a set of wind-speed intervals for which the corresponding set of states of preparedness represents a gradual closing down of the activities of the center in such a way as to minimize the interference with operations.

Some guidelines can be established for selecting the wind-speed intervals to incorporate in the hurricane plan. The following are proposed:

(1) Use equation (1B) to compute the upper 95% confidence bound, t, on the lead time required by each facility for each wind speed specified. Replace the three time estimates with this value.

(2) Determine for each wind speed the maximum value of t which occurs for any facility. Consider that this value represents the lead time required by the base for the wind speed in question.

(3) Compute for each wind speed the average loss in effectiveness for the facilities involved in missile testing.

(4) Determine the minimum wind speed for which at least some preparations are required. Use this minimum as the beginning of the wind-speed interval for the first (least severe) condition.

(5) Select wind-speed intervals on the basis of approximately equal lead times but with due consideration being given to the delay in loss in effectiveness for missile-testing facilities.

(6) Construct a tentative set of states of preparedness from the data thus derived.

Tables 1B and 2B were prepared to illustrate a possible outcome of the above procedures. Table 1B lists the maximum value of t required by any facility for each of the wind speeds considered and the average loss in effectiveness for each of the wind speeds. Table 2B represents a tentative set of states of preparedness such as might be derived from the data in Table 1B.

TABLE 1B

SUMMARY OF FACILITY SURVEY DATA (Sample)

| Sustained Wind Speed (kts) | Maximum Value of t' (hrs) | Average Loss in Effectiveness for Missile-testing Facilities (Accumulative %) |
|---|---|---|
| 20 | 0 | 0 |
| 25 | 0 | 0 |
| 30 | 6 | 10 |
| 35 | 6 | 20 |
| 40 | 12 | 35 |
| 45 | 12 | 65 |
| 50 | 6 | 100 |
| 55 | 6 | 100 |
| 60 | 0 | 100 |
| 65 | 0 | 100 |

TABLE 2B

A TENTATIVE SET OF STATES OF PREPAREDNESS (Sample)

| State of Preparedness ($i$) | Sustained Wind Speed (kts) ($s_i$ to $s_{i-1}$)* | Lead Time (hrs) ($t_i$) |
|---|---|---|
| 4 | 0 - 30 | 0 |
| 3 | 30 - 40 | 12 |
| 2 | 40 - 50 | 24 |
| 1 | 50 - | 12 |

* Up to but not including $s_{i-1}$

After a tentative set of states of preparedness has been constructed it should be submitted to all of the facilities for confirmation that each can meet the prescribed degree of preparedness within the specified lead time with a confidence of 95%. In case some facility reports that it cannot do so, then either the preparedness plan for that facility or the set of states of preparedness, or both, will have to be revised. In extreme cases it may even be necessary to enlarge the work force, or the resources, for such a facility.

FACILITY SURVEY FORM (PROPOSED)

Facility ________________ Function ________________

| Sustained[1] Surface Winds (kts) | Preparations Required[2] (additional) | Effectiveness Lost (Accum. % ) | Estimates of lead[3] Time Required (Hrs) m / b / c |
|---|---|---|---|
| 20 | | | |
| 25 | | | |
| 30 | | | |
| 35 | | | |
| 40 | | | |
| 45 | | | |
| 50 | | | |
| 55 | | | |
| 60 | | | |
| 65 | | | |

1. "Surface" winds are those winds at 10-15 ft. above ground level.

2. List only the additional preparations required for each wind speed. Do not forget to allow for gusts and for increases in wind speed with height.

3. Make three estimates - most likely (m), Optimistic (b), and pessimistic (c)

Enclosure (1) to Appendix B

## APPENDIX C. OBTAINING COST ESTIMATES

After the tentative set of states of preparedness has been confirmed by all facilities, the next step in the development of a hurricane plan is to conduct another survey--this time to obtain dollar cost estimates. The estimates needed are (1) the cost in establishing each state of preparedness given that the previous state has already been established, (2) the cost of unbuttoning (returning to normalcy) from each state, and (3) the anticipated cost of repairs, replacement, etc., if the facility were to be caught underprepared, i.e., caught by condition i winds while prepared for winds of condition i + 1.

A form to aid in the obtaining of the above cost estimates has been designed and is presented as enclosure (1). It should be noted that this form calls for three estimates of each kind of cost. The three estimates are:

(1) the most likely (m, v, and w),

(2) the optimistic (d, f, and h),

(3) the pessimistic (e, g, and k).

These are defined, respectively, as:

(1) the best estimate of how much the cost will actually be,

(2) the least the cost is likely to be, and

(3) the most the cost is likely to be.

In order to estimate the preparatory costs with any reasonable degree of accuracy it is mandatory that the estimators know exactly what preparations are to be accomplished for each state of preparedness. Accordingly, the preparations listed on the Facility Survey Form for the various wind speeds should be combined in accordance with the states of preparedness established by the coordinating agency and, if required, should be expanded into a more detailed form.

An important factor which will affect preparatory costs is that of overtime. The estimator will have to consider the various possibilities before deciding how much overtime is likely to be needed for each state of preparedness. However, due to the fact that Hurricane Advisories are normally issued at fixed times, some guidelines can be established for anticipating when the word will be announced to set a different state of preparedness. The most likely time for this to occur is probably 1200 EST, the best likely time is 0600 EST, and the worst likely time is 1800 EST.

Estimates of the unbuttoning costs should, naturally, be based upon the nature and extent of the preparations planned for each preparedness state. The amount of overtime required should be expected to be comparatively small as there will normally not be a great deal of urgency in connection with unbuttoning and full work days should be available.

The anticipated repair costs for damage to facilities because of underpreparation will be extremely difficult to estimate with any reasonable degree of accuracy. Nevertheless, it must be attempted as these costs are fundamental to the computation of the reference critical probabilities. The only guideline that can be offered here is that if the additional preparations which are indicated as being required for the successive state of preparedness are correct, then the kind and amount of damage to be expected for being caught underprepared can be approximated by consideration of the nature and extent of these preparations. From these damage approximations estimates of the repair costs can then be made.

After all facilities have completed their cost estimating, the next step is for the coordinating agency to combine these estimates to obtain total costs for the entire center for each preparedness state. Actually, we shall consider these costs to be random variables and shall compute their upper 95% confidence bounds. These confidence bounds are to be used for computing reference values for the critical probabilities.

There are fundamentally just two costs of concern; namely, (1) the additional cost which will be incurred if the next higher, that is, more severe, state of preparedness is set, and (2) the repair cost which will result if we are caught underprepared. The first cost consists of the sum of (a) the cost of the additional preparations required for the next higher state of preparedness and (b) the added cost of having to unbutton from the next higher state rather than from the current state. This first cost will be designated as the incremental buttoning-unbuttoning cost. The second cost is simply the anticipated repair cost which has already been described.

Let $u_{ij}$ represent the cost of completely unbuttoning the j<u>th</u> facility from the i<u>th</u> preparedness state. Then the incremental unbuttoning cost, $\Delta u_{ij}$, for the i<u>th</u> state for this facility would be

$$\Delta u_{ij} = u_{ij} - u_{(i+1)j} \quad .$$

Let $q_{ij}$ represent the cost of the additional preparations required by the j<u>th</u> facility for the i<u>th</u> preparedness state and, similarly, let $c_{ij}$ represent the incremental buttoning-unbuttoning cost. Then by definition

$$c_{ij} = q_{ij} + u_{ij} \ .$$

Assuming that there are n facilities, the upper 95% confidence bound on the incremental buttoning-unbuttoning costs for the ith preparedness state can be approximated by*

(1C) $$C_i = E(c_i) + 1.645 \ \sigma_{c_i},$$

where $c_i = \sum_{j=1}^{n} c_{ij}$ , $E(c_i)$ = the expected value of $c_i$,

and $\sigma_{c_i}$ = the standard derivation of $c_i$. Now

(2C) $$E(c_i) = \sum_{j=1}^{n} E(c_{ij})$$

and

(3C) $$\sigma_{c_i} = \sqrt{\sum_{j=1}^{n} \sigma^2_{c_{ij}}} \quad ,$$

where

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* It is assumed that the $c_{ij}$'s will be Beta distributed but that $c_i$ will be approximately normally distributed.

$$(4C)\quad E(c_{ij}) = E(q_{ij}) + E(\Delta u_{ij}),$$

$$= E(q_{ij}) + E(u_{ij}) - E(u_{(i+1)j}),$$

$$= \frac{d_{ij} + 4m_{ij} + e_{ij}}{6} + \frac{f_{ij} + 4v_{ij} + g_{ij}}{6} +$$

$$- \frac{f_{(i+1)j} + 4v_{(i+1)j} + g_{(i+1)j}}{6},$$

approximately, and

$$(5C)\quad \sigma^2_{c_{ij}} = \sigma^2_{q_{ij}} + \sigma^2_{u_{ij}} + \sigma^2_{u_{(i+1)j}},$$

$$= \left(\frac{e_{ij} - d_{ij}}{6}\right)^2 + \left(\frac{g_{ij} - f_{ij}}{6}\right)^2 + \left(\frac{g_{(i+1)j} - f_{(i+1)j}}{6}\right)^2,$$

approximately.

In a similar manner we obtain for the upper 95% confidence bound on the anticipated repair costs for the ith preparedness state for the jth facility

$$R_i = E(r_i) + 1.645\,\sigma_{r_i}\,, \tag{6C}$$

where

$$E(r_i) = \sum_{j=1}^{n} E(r_{ij}) \tag{7C}$$

with

$$E(r_{ij}) = \frac{h_{ij} + 4w_{ij} + k_{ij}}{6}\,, \tag{8C}$$

approximately, and

$$\sigma_{r_i} = \sqrt{\sum_{j=1}^{n} \sigma^2_{r_{ij}}} \tag{9C}$$

with

$$\sigma^2_{r_{ij}} = \left(\frac{k_{ij} - h_{ij}}{6}\right)^2\,, \tag{10C}$$

approximately.

Sets of hypothetical values for $C_i$ and $R_i$ were constructed for an exercise in computing reference values for the critical probabilities. These sets are presented in Table 1C. The formulas used for computing the reference values were

$$p_{ri} = C_i/R_i ,$$

and

$$p'_{ri} = \frac{\sum_{k=1}^{i} C_k}{\sum_{k=1}^{i} R_k}$$

TABLE 1C

UPPER 95% CONFIDENCE BOUNDS ON COSTS AND THE RESULTING REFERENCE VALUES FOR THE CRITICAL PROBABILITIES (hypothetical)

| State of Preparedness | Buttoning-Unbuttoning Cost (thousands $) | Anticipated Repair Cost (thousands $) | Reference Values for Critical Probabilities | |
|---|---|---|---|---|
| $i$ | $C_i$ | $R_i$ | $\hat{p}_{ri}$ | $p'_{ri}$ |
| 3 | 40 | 100 | .400 | .183 |
| 2 | 50 | 300 | .167 | .140 |
| 1 | 20 | 200 | .100 | .100 |

SURVEY FORM FOR OBTAINING COST ESTIMATES (PROPOSED)*

Facility ____________________

| State of Preparedness i | Sustained Surface Wind Speed (kts) | Lead Time (hrs) | Cost of Preparations[1] (thousands of $) | | | Unbuttoning costs[1,2] (thousands of $) | | | Anticipated Repair[1,3] Costs (thousands of $) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | m | d | e | v | f | g | w | h | k |
| 3 | 30-40 | 12 | | | | | | | | | |
| 2 | 40-50 | 24 | | | | | | | | | |
| 1 | 50- | 12 | | | | | | | | | |

1. Three estimates are desired--the most likely (m, v, and w), the optimistic (d, f, and h), and the pessimistic (e, g, and k).

2. Unbuttoning costs for each preparedness state should be those costs involved in returning completely to normalcy.

3. Estimate the anticipated repair costs on the basis that state i winds occur while the facility is prepared for state i + 1 winds.

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* The first three columns were filled in for illustration purposes only.

Enclosure (1) to Appendix C